DEVELOPMENT AND TUNING OF A 3-D STOCHASTIC INVERSION METHODOLOGY FOR THE EUROPEAN ARCTIC

Hilmar Bungum[1], Michael E. Pasyanos[2], Jan Inge Faleide[3], and Stephen A. Clark[3]

NORSAR[1], Lawrence Livermore National Laboratory[2], and University of Oslo[3]

Sponsored by National Nuclear Security Administration

DE-AC52-08NA28651[1,3], and DE-AC52-07NA28116[2]
Proposal No. BAA08-38

ABSTRACT

High-resolution seismic models are a critical component of calibrating earth structure for improved seismic monitoring. We will in this study develop the Markov Chain Monte Carlo (MCMC) inversion method into an even stronger tool for deriving reliable three-dimensional seismic models of the crust and upper mantle, based on multiple types of geophysical data sets. This will be done by tuning the method to the European Arctic through development of a probabilistic geophysical model. While a new and much improved model (BARENTS3D) recently has been developed for this region (Ritzmann et al., 2007), stochastic models have a potential to better represent our state of knowledge (and uncertainty) about geophysical structure because deterministic models do not express well the tradeoffs inherent in the data. Stochastic inverse methods also allow a more systematic exploration of the model space to help avoid the trap of falling into local minima. Finally, stochastic models allow prediction of observable distributions (and through them observable uncertainties).

In this project, we will use multiple data types, notably (i) surface-wave group velocities, (ii) regional body-wave travel times, (iii) gravity data, (iv) compiled 1D velocity models, and (v) thickness relationships between sedimentary rocks and underlying crystalline rocks, to develop the model by comparing predictions of the proposed models to the observed data. The Barents Sea region is ideally suited for such development and tuning of stochastic inversion techniques because: 1) multiple data types have already been assembled and much knowledge is available about the uncertainties in these data, 2) an excellent S-wave velocity model is available which can serve as a starting model (http://www.norsar.no/seismology/barents3d/) and as a foundation for the base sampler, 3) an ongoing UiO project on the Barents Sea region will provide additional a priori constraint on the starting model as well as a wider geologic context by which to assess the stochastic inversion results, and 4) the region encompasses test sites and several seismic stations and arrays, making it suitable to invest in more sophisticated forms of modeling. In the process of developing and implementing a new inversion methodology, the primary outcome of this study will be an improved seismic model with rigorously quantified uncertainties in parameters and observables.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Development and Tuning of a 3-D Stochastic Inversion Methodology for the European Arctic**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Lawrence Livermore National Laboratory,PO Box 808,Livermore,CA,94551-0808**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 30th Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies, 23-25 Sep 2008, Portsmouth, VA sponsored by the National Nuclear Security Administration (NNSA) and the Air Force Research Laboratory (AFRL)

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

OBJECTIVES

The main purpose of this study is to develop further the Markov Chain Monte Carlo (MCMC) methodology as applied to lithospheric velocity models. The stochastic MCMC approach is especially powerful for two reasons: it has the capability to utilize widely different types of data, such as seismological data and gravity in one inversion process; and it treats uncertainties in an advanced way, significantly improving upon conventional Monte Carlo and other inversion methods. In this study we will use the MCMC method on a variety of geophysical data sets to map the posterior probability distribution of the solution space of the model, with special emphasis on the joint inversion of gravity data and data from seismic methods such as group velocity maps.

The study area is the European Arctic, including the Barents Sea and surrounding regions such as the Norwegian-Greenland Sea, the southern Eurasian Basin, Novaya Zemlya and the southern Kara Sea, the East-European lowlands and the Kola Peninsula. Sediment thicknesses, crustal velocities, crustal thicknesses and upper mantle velocities vary widely across the area, leading to very complicated propagation of regional waves in the crust and upper mantle. By mapping the variation in seismic velocities in the region, we can calibrate the region for travel-time predictions and more accurate event locations, account for phase blockage and amplitude variations in phase association, and eventually model waveforms for template-matching analysis.

While 3D seismic velocity models for the greater Barents Sea region have been developed under previously funded studies (http://www.norsar.no/seismology/barents3d/), the emphasis in this effort is to use stochastic methods to characterize the model uncertainties and the uncertainties on predicting observables, such as the travel time of regional seismic phases. By capturing the model uncertainties and (importantly) their correlations, we will be able to reliably propagate the uncertainties into parameters derived using this model, such as seismic event locations using model-based travel times. While the information that each of these data sets are able to contribute individually will be used, they will also be combined in order to best determine the seismic structure of the whole region, and to provide reasonable uncertainty estimates on the structure. By implementing an MCMC methodology in the greater Barents Sea region, we will also produce a stronger tool for many other regions that are less well covered by data.

The main research objective of this study is therefore to further develop and tune the probabilistic MCMC inverse technique in a region that is well covered by multiple high-quality datasets, in particular, group velocity maps, travel-time data, and crustal-scale deep seismic data. A new high-resolution (ca. 50 km grid size) geophysical model for the European Arctic will then be a parallel product from this research. While a good velocity model already exists (Levshin et al., 2007), a mantle density dilemma, characterized by a high-velocity anomaly that is not seen in the gravity data, has revealed complex velocity-density relations in the upper mantle (Ritzmann and Faleide, 2008), that can only be solved by joint inversion of gravity and seismological data. The MCMC technique incorporates a variety of data sets, and through testing of thousands of models it allows a critical examination of the tradeoffs among model parameters.

Particular attention within this study will be given to the variability of models that are reasonable when fitting multiple data sets, and we will put emphasis on the assessment of the error bounds and the relative influence of the different data sets and their uncertainties. Such a rigorous assessment can only be quantified through extensive model testing. From a variety of possible models, we will carefully assess the interdependence of input parameters and establish the consequences for seismic event detection and event discrimination. Finally, the achieved knowledge will be transferred to other regional geophysical models (such as the Yellow Sea-Korean Peninsula region) aimed at elaborating their reliance on the basis of the backup constraints used. The region and the data sets selected for this study have been chosen because of their uniqueness, diversity, and high quality, which will allow us to develop the method further, in particular, by characterizing the ability of the method to capture both model and observable uncertainties.

RESEARCH ACCOMPLISHED

Since the present study has not yet started at the time of writing, this paper will essentially be based on the proposal, supplemented with some new data and results that have become available since the writing of the proposal.

Methodology and Approach

In this study we will be utilizing an advanced inversion technique to generate a well-constrained seismic model of the crust and upper mantle of the European Arctic, specifically, a stochastic inversion using the MCMC algorithm

(Figure 1). The stochastic method inverts data by probabilistically sampling the model space along one or more Markov Chains, comparing the observations predicted by the proposed model to the observed data, and preferentially accepting models that produce a good fit, thus generating a posterior distribution of models. The likelihood is mapped through a series of stages comparing proposed models to data, with Bayes' Theorem relating the prior and posterior distributions.

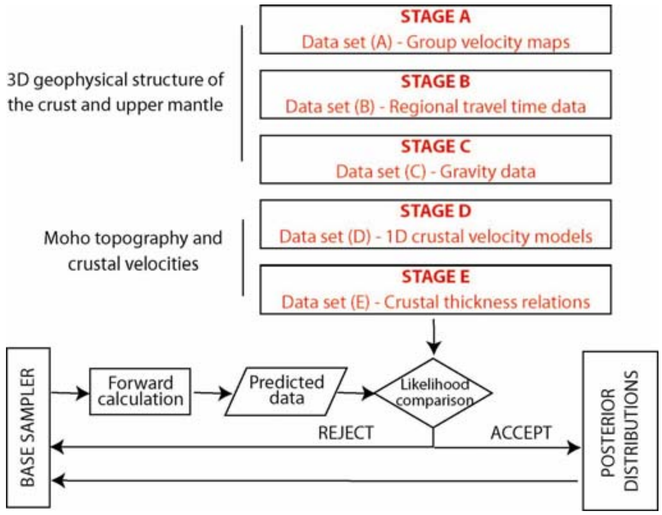

Figure 1. Schematic diagram of the stochastic MCMC inversion methodology, showing the algorithm for a multi-stage problem as intended in this study.

Each stage in the MCMC algorithm compares the proposed model to a different data type than the previous stages and, by properly ordering the stages, we can most efficiently search our parameter space. As the Markov Chains sample the model space, the posterior probability density function of the parameter space is mapped out. The stochastic method is able to produce a model that is able to reliably predict observations for a variety of geophysical data types.

The MCMC approach is a derivative of the Metropolis algorithm (Metropolis et al., 1953) as described by Mosegaard and Tarantola (1995). While specifics of the methodology can be found in Pasyanos et al. (2006), a brief outline is provided here. The first task in this methodology is to develop a "base sampler," a program that selects a proposed model, given the model parameterization and set of constraints that we can provide. This proposed model is a random (Monte Carlo) perturbation from the current state in the model space. Based on fits to the data (discussed below), the proposed model is either accepted or rejected. If a model is rejected, then we return to the previous model. If the model is accepted, however, then the base sampler will select the next model as a perturbation to the newly accepted model. In this way, we construct a Markov Chain to search the model space.

Whether or not we accept a model is based in part on how well predictions of the model compare to observations for a variety of data sets. If we always accepted a proposed model, then we would simply be sampling from our prior distribution. Instead, we base the acceptance on the fit of a proposed model to the observed data. For each data type, we use a likelihood function that includes the data predicted for a given model, a vector containing the observed measurements, and the estimated data uncertainty, based on an L2 norm. We decide whether or not to accept a model by comparing the respective likelihoods of the current and proposed models. After the Markov Chains have adequately sampled the model space, we are left with the distribution of models that is consistent with our observables and the uncertainties in our observables.

Geologic Setting

The study region (Figure 2) encompasses old cratonic crust, continental shelf regions, and oceanic crust. The oldest rocks, of Archean/Proterozoic ages, are found on the Kola Peninsula and nearby regions and occur within a patch of ancient terrains. The Caledonian Orogen extends along western Norway and is subdivided into four tectonic nappes. Obduction started in the Vendian to Middle Cambrian and lasted until the Silurian.

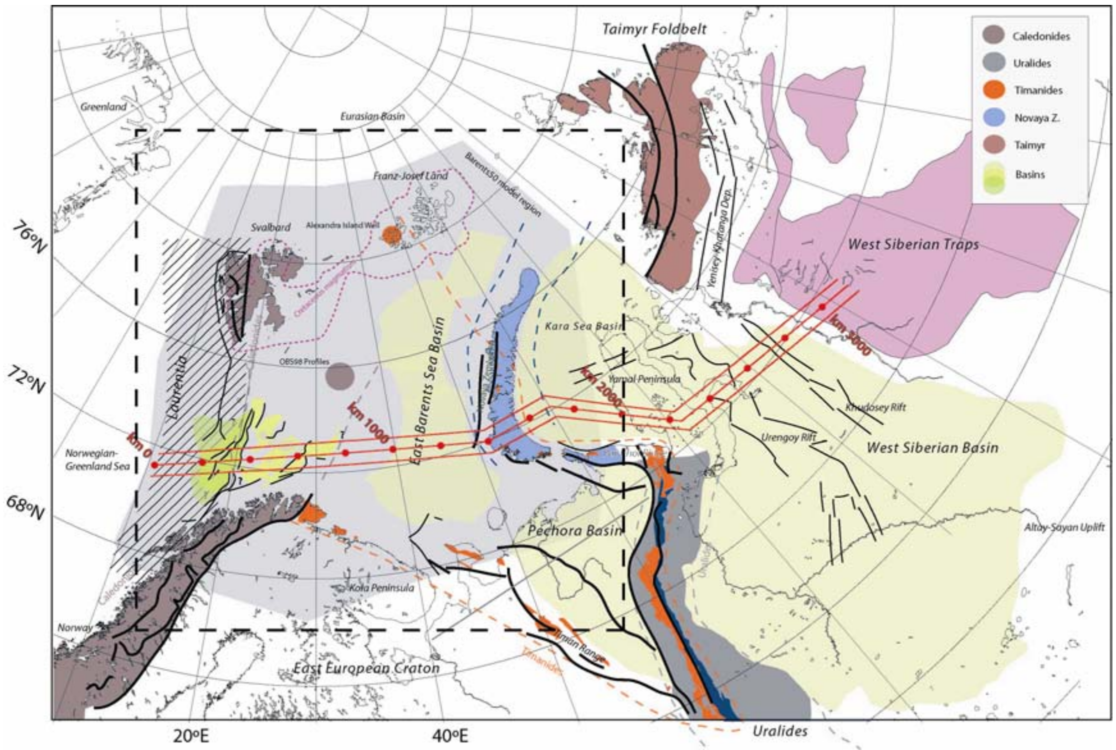

Figure 2. Map of the greater Barents region with main geological features (after Ritzmann and Faleide, 2008). The black dashed box indicated the target region for this study. Thick red lines show the location of the transect in Figure 3.

Caledonian main thrusts, striking N and NE, are also revealed in the western Barents Sea (Ritzmann and Faleide, 2007). After the Caledonian orogenic collapse, the western Barents Sea experienced widespread Paleozoic- and Mesozoic/Paleocene rifting along the N/NE-trending Caledonian basement grain. During the Early Cretaceous rift phase, some of the basins in the western Barents Sea region subsided more than 12 km, leading to a total sedimentary succession at present of more than 20 km. Similar deep sedimentary basins are observed in the eastern Barents Sea, to the west of the (most likely) Late Triassic-Early Jurassic Novaya Zemlya Fold Belt.

The nature of the underlying crystalline crust and upper mantle in the eastern Barents Sea basins is still a matter of debate, since some authors propose an oceanic crustal nature. Generally, the deformation style in the western (more brittle) and eastern (more flexural) Barents Sea is very different. Cretaceous magmatism is evident to the east of the Svalbard Archipelago. Seafloor spreading in the Norwegian-Greenland Sea and the Eurasian Basin started in Early Eocene times. The western continental margin of today consists of a series of sheared and rifted margin segments. A comprehensive and referenced geological overview can be obtained from Ritzmann et al. (2007).

Recent results established a high-velocity body in the upper mantle below the eastern Barents Sea Basin, Novaya Zemlya, and the Kara Sea (Figure 3). The high-velocity body has about a 100-km thickness and reveals a slight dip towards the east. Early interpretations regarded this structure as a remnant of a subducted slab (Levshin et al., 2007). However, seismic velocities of peridotite mantle rocks, along a standard continental geotherm, are considerably lower than those observed here (Cammarano et al., 2003). Seismic velocity anomalies within the upper mantle are predominantly caused by temperature variations, rather than compositional effects (Goes et al. 2000). This, in turn, leads to the assumption that the eastern Barents Sea is underlain by a cold cratonic keel similar to the Siberian Craton (Ritzmann and Faleide, 2008).

This concept gets additional support from simple 2D gravity modeling. Neither the free-air gravity, nor the geoid, show a pronounced, long-wavelength (ca. 1,000 km) anomaly across the eastern Barents Sea (Ebbing et al., 2007; Ritzmann and Faleide, 2008), suggesting a simple, horizontally layered mantle density structure. Density contrasts due to temperature variations below cratons are presumed to be entirely compensated by Al/Fe depletion

(weight loss), and hence no lateral density variations are observed at cratonic boundaries. The upper mantle density structure of BARMOD (Levshin et al. 2007) and CUB1.0 (Shapiro and Ritzwoller, 2002) is calculated from seismic velocities, using fixed heterogeneity ratios. This technique violates significantly the findings from the gravity modeling, since velocity changes are obviously not simply proportional to density changes (Ritzmann and Faleide, 2008). Thus, the joint inversion of seismological data and gravity data planned in this study is essential to achieve a reasonable upper mantle geophysical and compositional structure.

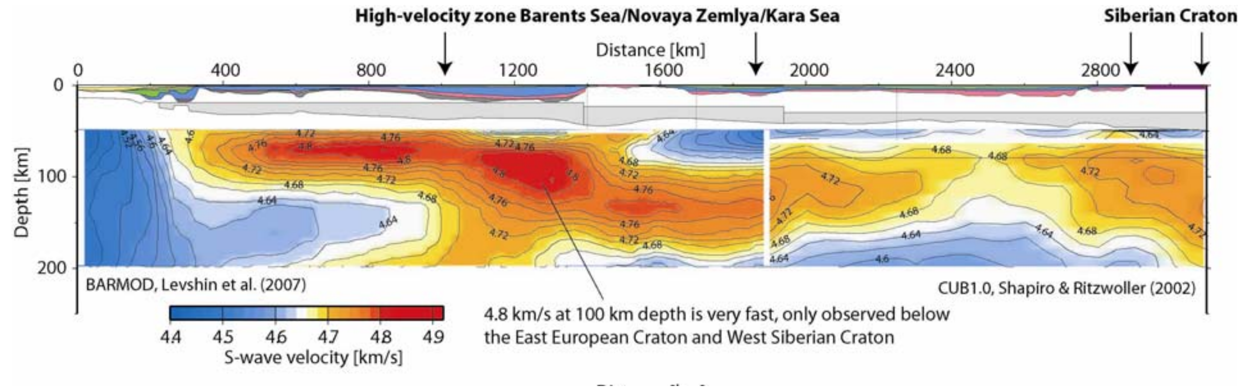

Figure 3. West-East transect from the Norwegian-Greenland Sea (left) across the Barents Sea to Novaya Zemlya (km 1,500) and the Siberian Craton (right). The panel shows absolute S-wave seismic velocities (Levshin et al., 2007). Profile location shown in Figure 2.

Model Development

The Barents Sea–Novaya Zemlya region is interesting both from a geophysical and a seismic verification point of view. A largely DOE funded study was completed in 2005 in which 3D seismic velocity models both for the crust (BARENTS50) and the upper mantle (BARMOD) were developed, using a grid density of 50 km and one degree, respectively (Levshin et al., 2007; Ritzmann et al., 2007). Figure 4 shows a Moho map of the BARENTS50 crustal model, which will be used as a starting model in this study.

Levshin et al. (2007) searched for new surface wave data set in the European Arctic and retrieved observations from regional data archives in Norway, Finland, Denmark, and Russia in addition to data from the data centers of IRIS and GEOFON. Rayleigh and Love wave group velocity measurements between a 10 and 150 s period were combined with existing data provided by the University of Colorado at Boulder. This new data set was inverted for maps showing the 2D group-velocity distribution of Love and Rayleigh waves for specific periods. Using a Monte Carlo inversion technique (Shapiro and Ritzwoller, 2002), they constructed a new 3D shear-velocity model of the upper mantle using the crustal BARENTS50 model as a backup constraint.

The basic principle of the model development is to stochastically propose a 3D geophysical structure and compare this subsequently to available data sets. Generally, we acquired the following data sets: (A) group velocity maps based on a comprehensive set of recordings, (B) regional travel time data, (C) gravity data, (D) 1D crustal velocity models (sampled from 2D profiles), and (E) regionally dependant thickness relations between the sediment and crystalline crustal thickness. Sets (A) to (C) constrain the entire lithosphere, while (D) and (E) explicitly constrain the local crustal structure.

All of our compiled data sets are independent of each other. We can use the group velocity maps and the gravity data to infer the geophysical parameterization (velocity, density) while we use the thickness relation and regional travel time data to map more locally the crust-mantle boundary topography, which can cause travel time differences of up to several seconds. In the following sections, we will describe the different data sets that we plan to use in producing the model. The exact order of the data sets in the inversion will be optimized to increase the efficiency of the stochastic inversion. Our next step is then comparing the observations of proposed models to data.

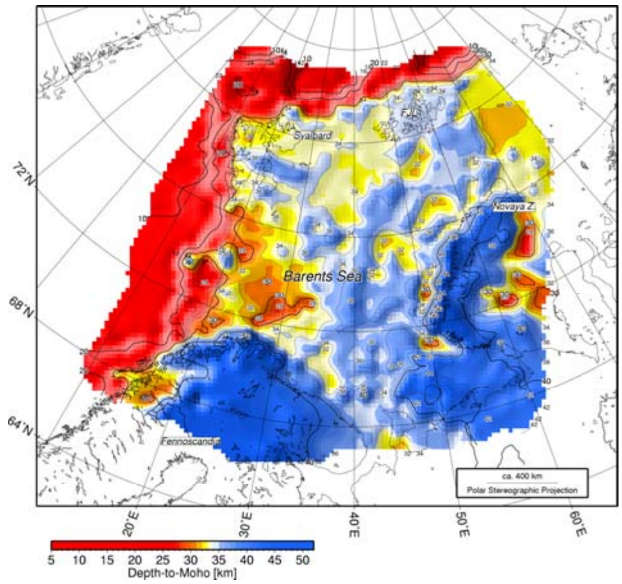

Figure 4. Moho depth map for the main target area in the greater Barents Sea region (Ritzmann et al., 2007).

Set (A): Comparison with group velocity data

The first set of parameters we will employ are measurements of surface-wave dispersion. We actually have two sets of group velocity measurements available for use in this region. The first one of these is from a study based on a combined University of Colorado and NORSAR data base that resulted in the BARMOD model (Levshin et al., 2007), based on Love and Rayleigh wave data between 1970 and 2005. The data cover periods between 10 and 150 s, and there are around 2,500 paths at a period of 30 s. Figure 5 shows group velocities from the combined NORSAR and Universities of Colorado (CU), Oslo, and Paris study (Levshin et al., 2007).

The surface-wave data are a very good indicator of average velocity structure, although, unlike some of the body-wave phases, surface-waves are not particularly sensitive to pronounced velocity/density gradients. Surface waves are also very good at covering aseismic regions or non-instrumented regions that are not similarly well covered by body-wave phases. Since our target region is located offshore, a regional body-wave tomography model would require the deployment of an ocean-bottom seismometer grid, which is not planned nor expected within the near future.

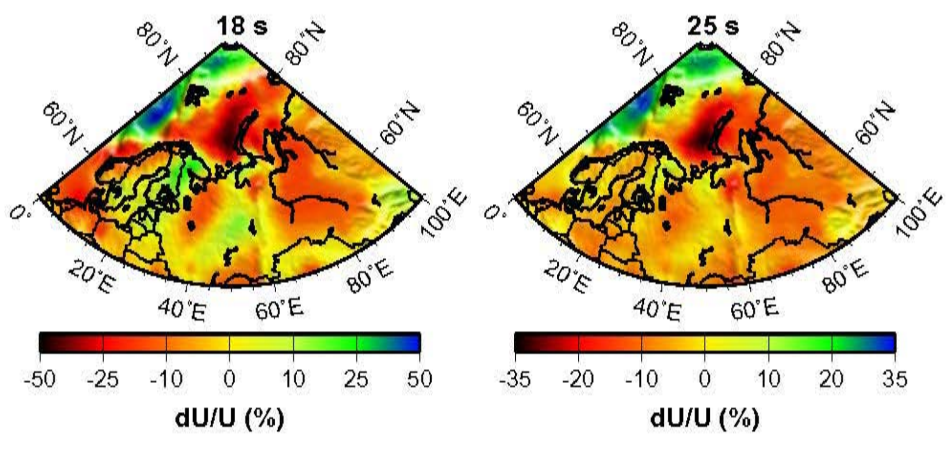

Figure 5. 2-D distribution of inverted group velocities, presented as deviations from the average velocity, for periods of 18 and 25 s (Levshin et al., 2007).

Set (B): Comparison with regional travel time data

Data set B, chosen for comparison of proposed models with constraints, consists of travel time data from analyst picks, and here we have two different datasets. The primary set of such data includes a comprehensive collection of reference events, including GT (ground truth) events, collected and analyzed by NORSAR (Maercklin et al., 2007). Besides *Pn* and *Pg* readings, the database also contains a comprehensive collection of *Sn* and *Lg* phases, and these will be used in this study.

For some of these data there are quality problems related in part to epicenter precisions but also to timing errors at the seismic stations. One of the advantages with the stochastic inversion methodology is, however, that the uncertainties in the input data can be properly accounted for. Many active seismic experiments have been additionally observed by the International Monitoring System auxiliary array SPITS (e.g., Schweitzer, 2000), and these absolute travel time observations will be added as GT-0 observations to the database.

Set (C): Gravity data

After passing the likelihood comparison for the lithospheric P-and S-wave velocity structure (group velocity maps and travel-time data) the subsequent test targets the density structure. The regional gravity field will be calculated on the basis of the stochastically proposed 3D density structure and compared to the observed gravity field.

Gravity data (free-air) are freely available from various recent projects, such as the Arctic Gravity Project (http://earth-info.nga.mil/GandG/wgs84/agp/) and the GRACE experiment (gravity recovery and climate experiment; Tapley et al. 2005). The free-air gravity anomalies in the Barents Sea/Kara Sea region are mostly very smooth (-50 to +20 mgal; Figure 6). Notable exceptions are the up to 20-km-deep sedimentary basins and adjacent basement highs in the western Barents Sea, which provide gravity signals of up to 100 mgal. Interestingly, the 20 km deep East Barents Sea Basin (east of 40°E) is not characterized by a broad regional gravity low, suggesting a deeper-seated local compensation.

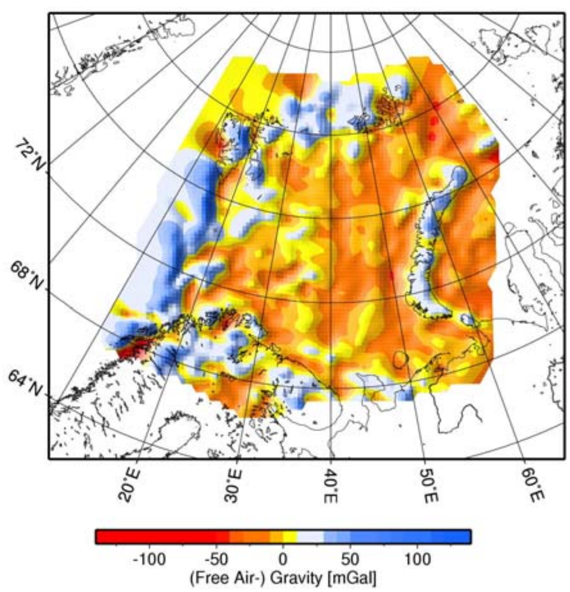

Figure 6. Free air gravity data in the target region (http://earth-info.nga.mil/GandG/wgs84/agp/).

Again we mention the misleading concept that density is proportional to seismic S-wave velocity below the eastern Barents Sea. As stated earlier, the thermal state of the upper mantle in the target region is likely to be cold and possibly cratonic (Ritzmann and Faleide, 2008). This infers high seismic velocities and low densities due to chemical depletion. Any amplitude modeling performed with existing models (1D-BAREY, 3D-BARMOD) are thus based on overestimated densities causing excessively high impedance contrasts, for example, at the crust-mantle boundary or at the lithosphere-asthenosphere boundary. The joint inversion of the density structure is therefore a very important part of this project.

Set (D): 1D crustal velocity profiles

In this study we will use vertical 1D velocity profiles compiled from 2D models (Figure 7) to constrain the velocity structure directly beneath and in close vicinity to seismic stations. In all, there are 620 1D velocity-depth profiles comprising the existing database (Ritzmann et al., 2007). While most of the profiles are for P-wave velocities, some S-wave profiles are also included. The data constraint derives from deep seismic reflection profiles as well as wide-angle OBS surveys.

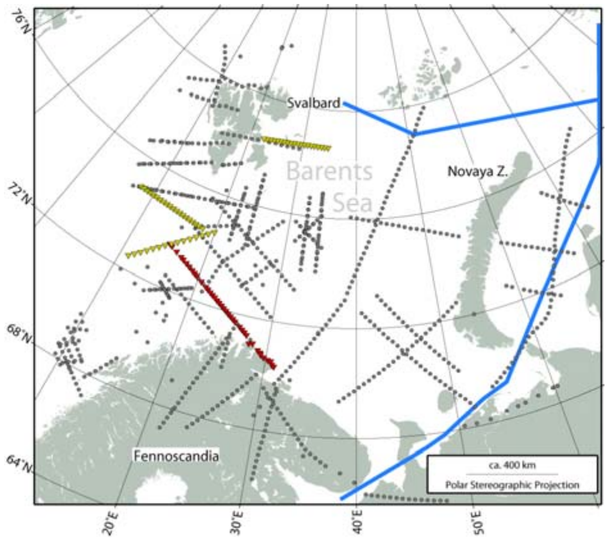

Figure 7. Distribution of 1D seismic profiles for the crustal column used as constraint in the BARENTS50 3D model (grey circles; after Ritzmann et al., 2007). New deep seismic surveys providing additional constraint were recently published (blue), acquired in 2007 (red), or planned for 2008 (yellow).

Set (E): Regionally dependent thickness relations

A crucial observation during the construction of the BARENTS50 crustal model (Ritzmann et al., 2007) was the regional dependence of sediment thickness relative to the thickness of the crystalline crust (Figure 8). On the basis of the state-of-the-art geological knowledge of the Barents Sea, separate geological provinces were defined. These provinces are local and regional sedimentary basins, basement horsts, or units overprinted by volcanic activity. The 620 1D velocity profiles were assigned to these provinces, and the sediment thickness was plotted against the thickness of the crystalline crust. Figure 8 shows the result for eight of these provinces.

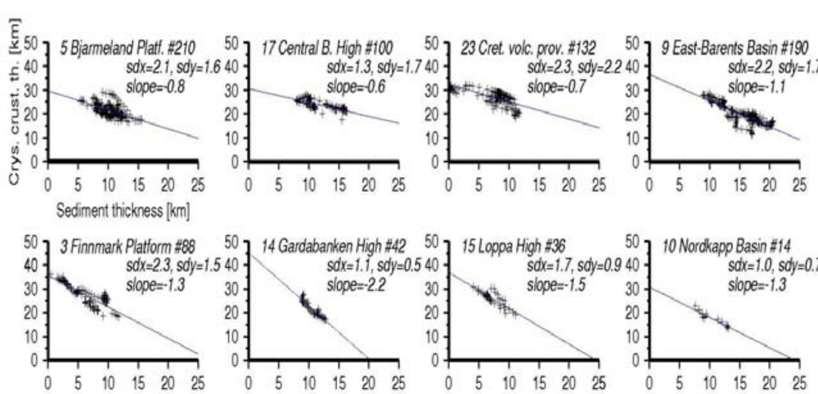

Figure 8. Eight characteristic examples of thickness relations in the Barents Sea region. The x-axis shows the sediment thickness, while the y-axis shows the crystalline crustal thickness.

The data can be sufficiently fitted by linear regressions with province-dependent slopes and intercepts (Figure 8). Since a regional sediment thickness map is available (compiled in Ritzmann et al., 2007), we were able to infer the crystalline crustal thickness from the sediment thickness at any node in the model. This is especially important in regions with limited data constraint, such as the northeastern Barents Sea. Here, the characteristic relationships help to infer the probable Moho depth by summation of the sediment thickness and the remaining 'crystalline' thickness inferred by using the regression parameter. In turn, all MCMC-proposed (crustal) models that are not in accordance with this observation fail the test. These data will be employed in a manner similar to the 1D velocity profiles, by assessing the misfit of proposed models to the depth-to-basement data and regression parameters.

Uncertainty considerations

One important component of this study is in assessing uncertainties on both the seismic models and on observables. The MCMC stochastic inversion methodology makes it relatively easy to assess the uncertainties of seismic models, since the technique maps out the probability distribution of the models. Uncertainties on observable parameters, such as travel times, can be assessed by calculating the travel times through all of the models in the posterior distribution, or some fraction of the models.

Each phase has a range of travel times associated with them, some of which appear to be skewed rather than simply normally distributed. While the overall distribution of travel times for each phase would ideally be used in locations, if necessary, the distributions could in some cases be approximated by a normal distribution or a sum of normal distributions. We would like to assess whether the uncertainties of the observables predicted from the model are consistent with the uncertainties of our input data sets. This assessment can only be accomplished with the high quality travel time data available in this project.

New Data and Results Available from the Barents Sea

As part of the recently launched Petroleum-related studies of the Barents Sea Region (PETROBAR) project coordinated by UiO, new wide-angle seismic profiles have been and will be acquired in the boreal summer seasons of 2007 and 2008. In 2007 an OBS survey was carried out along an existing deep seismic reflection profile in the SW Barents Sea (Figure 7, red profile). Planned for 2008, another PETROBAR OBS profile will be acquired east of Svalbard, as well as two OBS profiles across the western Barents Sea margin adjacent to Bear Island (Figure 7, yellow profiles) as part of an International Polar Year project coordinated by NORSAR.

Further, wide-angle seismic data were recently acquired and published by several Russian researchers (e.g., Ivanova et al., 2006; Sakoulina et al., 2007; Roslov et al., 2008; for locations, see Figure 7, blue profiles). Therefore we will be able to extend the database for 1D profiles continuously and enable an even better crustal profile coverage than was available for the BARENTS50 model.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the MCMC stochastic inversion method seems to be a promising way of building seismic models and quantifying uncertainties in the European Arctic, with potential for wider application in other locations. We look forward to implementing this methodology on our unique dataset for the region and presenting our results at future meetings.

ACKNOWLEDGEMENTS

Due to the late start-up of the project, the present paper has been written largely on the basis of the proposal. As such, we are indebted to a number of people who took part in that process. First of all, Oliver Ritzmann, from the University of Oslo (UiO), was a key person in the earlier (2003-2005) DOE Barents Sea study, and was a driving force behind the present proposal. We also appreciate very much that data and results from an ongoing UiO Barents Sea study (PETROBAR), funded by the Research Council of Norway and StatoilHydro, has already been made available for the present study.

REFERENCES

Cammarano, F., Goes, S., Vacher, P., and Giardini, D. (2003). Inferring upper mantle temperatures from seismic velocities, *Phys. Earth. Planet. Int*. 138: 197–222.

Ebbing, J., Braitenberg, C. and Wienecke, S. (2007). Insights into the lithospheric structure and the tectonic setting of the Barents Sea region by isostatic considerations. *Geophys. J. Int.* 171: 1390–1403, doi: 10.1111/j.1365-246X.2007.03602.x.

Goes, S., Govers, R., and Vacher, P. (2000). Shallow mantle temperature under Europe from P and S wave tomography, *J. Geophys. Res*. 105: (B5), 11153–11169.

Ivanova, N. M., Sakoulina, T. S., and Roslov, Yu.V. (2006). Deep seismic investigations across the Barents-Kara region and Novozemelskiy Fold Belt (Arctic Shelf). *Tectonophysics* 420: 123–140, doi: 10.1016/j.tecto.2006.01.011.

Levshin, A., Schweitzer, J., Weidle, C., Shapiro, N., Maercklin, N., and Ritzwoller, M. (2007). Surface wave tomography for the Barents Sea and Surrounding Regions, *Geophys. J. Int*. 170: 441–459, doi:10.1111/j.1365-246X.2006.03285.x.

Maercklin, N., Ritzmann, O., Bungum, H., and Faleide, J.I. (2007). A seismic velocity model for the greater Barents Sea region: Reference events and travel time modeling. Unpublished manuscript.

Metropolis, Rosenbluth, N.A., Rosenbluth, A., Teller, A., and Teller, E. (1953). Equations of state calculations by fast computing machines, *J. Chem. Phys*., I, 1087–1092.

Mosegaard, K. and Tarantola, A. (1995). Monte Carlo sampling of solutions to inverse problems, *J. Geophys. Res*., 100, 12,431–12,447.

Pasyanos, M. E., Franz, G. A., and Ramirez, A. L. (2006). Reconciling a geophysical model to data using a Markov Chain Monte Carlo algorithm: An application to the Yellow Sea-Korean Peninsula region, *J. Geophys. Res.* 111: B03313, doi:10.1029/2005JB003851.

Ritzmann, O., Maercklin, N., Faleide, J. I., Bungum, H., Mooney, W. D., and Detweiler, S. T. (2007). A 3D geophysical model for the crust in the greater Barents Sea region: Model construction and basement characterization. *Geophys. J. Int*. 170: 417–435, doi: 10.1111/j.1365-246X.2007.03337.x.

Ritzmann, O. and Faleide, J. I. (2007). Caledonian basement of the western Barents Sea. *Tectonics* 26: TC5014, doi:10.1029/2006TC002059.

Ritzmann, O. and Faleide, J. I. (2008). The crust and mantle lithosphere in the Barents Sea/Kara Sea region. *Tectonophysics*, TECTO 124236, doi: 10.1016/j.tecto.2008.06.018.

Roslov, Yu.V., Sakoulina, T. S., and Pavlenkova, N.I. (2008). Deep seismic investigations in the Barents and Kara Seas. *Tectonophysics*, TECTO 124225, doi: 10.1016/j.tecto.2008.05.025.

Sakoulina, T. S., Verba, M. L., Ivanova, N. M., Krupnova, N. A. and Belyaev, I. V. (2007). Deep structure of the northern part of the Barents-Kara region along the transect 4-AR (Taimyr Peninsula-Franz Josef Land Arch. In: "*Models of the earth's crust and upper mantle*", papers of the International Symposium, St. Petersburg 18–20 September 2007, VSEGEI-Press, 197–200 (in Russian).

Tapley, B., Ries, J., Bettadpur, S., Chambers, D., Cheng, H., Condi, F., Gunter, B., Kang, Z., Nagel, P., Pastor, R., Pekker, T., Poole, S., and Wang, F. (2005). GGM02 - An improved Earth gravity field model from GRACE", *J. Geodesy*, doi:10.1007/s00190-005-0480-z.